THE HYBRID OF FLOATING STONE COLUMN BY NUMERICAL AND PHYSICAL EVALUATION

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ABSTRACT

Rapid population growth amplifying demand for accommodation and infrastructure has resulted in soft ground being increasingly used in construction. Problems related to soft ground can be remedied by adopting a ground improvement technique. The stone column is one of the most effective and feasible techniques for soft clay soil improvement. Stone columns increase bearing capacity and reduce the settlement of soil. However, soft ground of more than 40 meters depth makes stone column treatment costlier. The design of floating stone columns within soft ground is sometimes needs to adopt. However, this method is not popular compared to the end bearing stone columns due to low mobilised shear resistance and resulted in higher occurrence of punching failure. This research is aimed for addressing the shortcoming floating stone columns with proposing the hybrid dimension floating stone columns. The hybrid stone column size able to increase the mobilised shear resistance, decrease punching failure, and reduce the volume of aggregates. In the present work, finite element analysis was performed using the program PLAXIS 2D. An elastic-perfectly plastic constitutive soil model relation based on the Mohr-Coulomb criterion was utilized to predict the behaviour of soft clay strengthen by stone column. Response Surface Methodology (RSM) was used to optimize the hybrid stone column size with the Design-Expert 6.0.4 software. The laboratory physical model tests were performed based on the sizes of optimum hybrid stone column size proposed by RSM. The results revealed that the optimal parameter of the uniform diameter of 44 mm with a length of 100 mm increases its load bearing capacity of 3260.7 N and the lowest settlement was recorded at a diameter of 24.2 mm with a length of 400 mm to achieve 25.8 mm of settlement. Moreover, the hybrid column size i.e. the first stone column diameter of 43 mm and second diameter of 21.2 mm with the same lengths of 200 mm each diameter able to achieve load-bearing capacity of 3350.9 N and settlement of 24.5 mm. Thus, by comparing with the uniform diameter stone column of 44 mm and length of 400 mm, the hybrid column able to increase the load bearing capacity by 3% and decrease the settlement by 5%. In addition, a good agreement was obtained between the numerical and physical models with variation 25%. In addition, the hybrid stone column size is able to reduce the volume of aggregates up to 40%.

ABSTRAK

Pertumbuhan penduduk yang pesat meningkatkan permintaan untuk perumahan dan infrastruktur telah mengakibatkan kawasan tanah lembut semakin banyak digunakan dalam pembinaan. Masalah yang berkaitan dengan tanah lembut boleh diperbaiki dengan menggunakan teknik penambahbaikan tanah. Tiang batu adalah salah satu teknik yang paling berkesan dan boleh dilaksanakan untuk pembaikan tanah yang lembut. Tiang batu meningkatkan keupayaan galas dan mengurangkan pemendapan tanah. Bagaimanapun, tanah lembut berkedalaman melebihi 40 meter menjadikan kaedah rawatan tiang batu mahal. Reka bentuk tiang batu terapung dalam lapisan tanah lembut kadang-kadang perlu digunakan. Walau bagaimanapun, kaedah ini tidak popular berbanding dengan kaedah tiang batu galas hujung kerana rintangan ricih rendah dan mengakibatkan kegagalan tebuk. Kajian ini bertujuan untuk menangani kekurangan tiang batu terapung dengan mencadangkan dimensi hibrid tiang batu terapung. Saiz tiang batu hibrid mampu meningkatkan rintangan ricih, mengurangkan kegagalan tebuk, dan mengurangkan jumlah agregat. Dalam kerja ini, analisis unsur terhingga dilakukan dengan menggunakan program PLAXIS 2D. Hubungan model tanah konstitutif plastik yang elastik berdasarkan kriteria Mohr-Coulomb digunakan untuk meramal kelakuan tanah lembut yang dikukuhkan dengan tiang batu. Response Surface Methodology (RSM) digunakan untuk mengoptimumkan saiz tiang batu hibrid dengan perisian Design-Expert 6.0.4. Ujian makmal model fizikal dilakukan berdasarkan ukuran saiz tiang batu hibrid yang optimum seperti dicadangkan oleh RSM. Hasilnya menunjukkan bahawa untuk meningkatkan kapasiti galas beban tiang batu yang optimum bagi reka bentuk bersaiz diameter seragam dicatatkan pada diameter 44 mm dengan panjang 100 mm untuk mencapai kapasiti galas beban 3260.7 N dan pemendapan terendah dicatatkan sebanyak 25.8 mm pada tiang batu berdiameter 24.2 mm dengan panjang 400 mm. Selain itu, bagi saiz tiang batu hibrid bagi tiang batu diameter pertama 43 mm dan diameter kedua 21.2 mm dengan panjang siap satu 200 mm mampu mencapai

kapasiti menanggung beban 3350.9 N dan pemendapan 24.5mm. Oleh itu, dengan membandingkan tiang batu seragam berdiameter 44 mm dan panjang 400 mm, tiang batu bersaiz hibrid mampu meningkatkan kapasiti beban galas sebanyak 3% dan mengurangkan pemendapan sebanyak 5%. Di samping itu, keputusan yang baik diperolehi antara model-model berangka dan fizikal, dengan perbezaan keputusan sebanyak 25%. Tambahan pula penggunaan tiang batu bersaiz hibrid mampu mengurangkan jumlah agregat hingga 40%.

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CHAPTER 1

INTRODUCTION

1.1 Background

The load-bearing capacity of soft soils presents one of the greatest challenges for geotechnical professionals due to its low bearing capacity and the fact that it exhibits large settlement when it is subjected to loading. Geotechnical conditions are part of the geological conditions which exist close to the ground surface and they are more associated with construction and human activities (Alpaslan, Bilge, and Mehmet, 2002; Han, 2015). At a time of urbanisation, rapid growth of the population and an increasing demand for development (such as houses and infrastructures) have resulted in unavoidable construction activities on soft ground instead of hard ground due to unavailability of suitable land (Hezmi, Rashid, and Alel, 2015). Thus, an engineer has to modify the ground based on the technical requirements for each project (Zomorodian, Ali, and Abolfazle, 2005). The soft ground must be remediated to achieve its suitability design load before any execution of construction activities (Naik, 2013). There are certain techniques are based on the project requirements in order to increase the bearing capacity, reduce settlement and/or to control groundwater and thus increasing the overall stability of the construction (Raju and Valluri, 2008; Shivashankar *et al.*, 2010).

Ground improvement is adopted in problematic soils and under difficult geotechnical conditions (Han, 2015). In the last 25 years, essential new soil remediation techniques have been developed to stabilise the ground as cost-effective solutions for constructions on difficult sites (Madun, 2012; Han, 2015). Many recent developments in materials, equipment and design methods have made ground improvement technologies to be more economical, efficient and effective (Curtin *et al.*, 2006). However, the state of affairs for most ground improvement technologies is one practice that is ahead of theory. Some researchers have developed their proprietary technologies, design methods and construction techniques to enhance their competitive advantage and edge over other construction firms (Nicholson, 2014). Most of the existing studies on ground improvement are focused primarily on the concept, application and individual case studies. However, a few books have been devoted to the principles and design methods of ground improvement (Kirsch and Kirsch, 2016). One of the most significant and current discussions in legal and moral philosophy is the selection of a suitable technique based on several factors, for instance, improving the ground condition and controlling the cost, social and environmental aspects of the projects which are critical factors for consideration (Egan and Slocombe, 2010; Ing *et al.*, 2012). Different terminologies have been used in the literature for ground improvements including soil improvement, soil stabilisation, ground treatment and ground modification. The term “ground improvement” has been commonly used both in literature and practice (Leung, Yee, and Leong, 2015). One of the extensive ranges of ground improvement methods for thicker soft ground is stone column. It is often considered as an environmental friendly method due to its easiness in removing and replacing existing materials in selected manner (Aza and Kalumba, 2014; Meghzili *et al.*, 2017).

The stone column method of ground improvement is known to be effective in enhancing the slope stability for both natural slopes and embankments by increasing the load-bearing capacity and accelerating the settlement. The first stone column was used in France by military engineers in the nineteenth century (McKelvey and Sivakumar, 2000; Meghzili *et al.*, 2017). Since then, stone columns have become one of the most globally used and most common ground improvement method in the UK (Serridge, 2006). Stone columns are usually adopted in light structural foundations, embankment stability and in controlling the liquefaction tendency in seismic areas (McKelvey and Sivakumar, 2000; Bell, 2004). This method is suitable for problematic ground that consists of soft cohesive soils (McCabe and Bryan, 2009). In recent times, the usage of this method has become more prominent. However, the installation of stone column is always designed to be reached at stiff layer which has the shear strength of more than 50 kPa. This is termed as fully penetrating columns or end bearing columns. A critical point that must be looked into before any installation of stone columns is that the column installation in very deep weak soil below a shear strength of 30 kPa is usually uneconomical (Shahrokhifard and Poursalehan, 2015). Therefore, partially penetrating columns or floating columns with toe embedded within clay soil layer are sometimes used even though the design of the floating column has not yet well understood compared to the end bearing columns.

Stone column is traditionally applied to support extensive loading using a large unlimited stone column groups (McCabe and Bryan, 2009; Al Ammari, 2016). However, its application has been expanded to stabilise the isolated strip footings and pad using small group arrangements in recent years (Kelly, 2014). Presently, the design practices are founded on the unit cell whereby it is suggested that each stone column in the group acts separately (Priebe, 1995). Several significances related with stone column design have originated from an understanding grown through reduced scale physical model tests (Kelly, 2014). In case studies, the evaluations of stone column performances can be conducted by using laboratory tests and finite element analysis (Kirsch and Sondermann, 2003). In addition, Narasimha, Prasad, and Hanumanta R (1992), Ambily and Gandhi (2007), Pivarč (2011) and Aza and Kalumba (2014) successfully validated the performance of stone column by comparing the finite element analysis using Plaxis 2D and the laboratory testing via adoption of the unit cell approach and the Mohr-Coulomb criterion for both soft clay and stone column. A work made by Balaam and Booker (1981) investigated the settlement behaviour of foundation supported by columns designed in soft clay for three different stone column pattern arrangements by using the unit cell technique. Narasimha *et al.* (1992) implemented a series of laboratory tests load on model stone columns used to stabilise marine soft clays in a large Triaxial cell. In the tests, there were three different lengths and diameters for the stone column selected and it was discovered that the lengths of the column were asymptotic with the amount of bearing capacity. Sivakumar *et al.* (2004) suggests that the optimum length of the stone column of at least five times the diameter of the stone column will not increase its bearing capacity but it can reduce the settlement. As a result, many researchers such as Sivakumar *et al.* (2007), Black, McNeill, and McCabe (2007), Killeen (2012) and Kelly (2014) conducted research on the floating stone column to prove that an increment in the column diameter will lead to the bearing capacity increment. On the contrary, an increment in the column length leads to the settlement decrement.

Plaxis software for finite element analysis is the most used software package in geotechnical engineering (Brinkgreve and Broere, 2015). The software (Plaxis) shows three dimensional (3D) finite element modelling of a vertical load system (Becker, 2013). According to Killeen (2012) and McCabe, Bryan, and Sheil (2014), 3D finite element modelling is often not practical to indicate the behaviour of a stone column. However, a two-dimensional (2D) axisymmetric model is sufficient to examine the stone column characteristics. There are several constitutive models such as Mohr-Coulomb model, the Hoek-Brown failure criterion, the double-yield model, the strain hardening/softening model and the ubiquitous-joint model provided in Plaxis. They are classified into elastic and plastic model groups (Hicher and Shao, 2013). The Mohr-Coulomb model is a familiar model used to represent shear failure in soils and rocks. It is extensively used in finite element analysis for geotechnical applications due to its simplicity and accurate outputs (Aliabadian and Sharafisafa, 2014). In this study, the laboratory test results integrated with the Mohr-Coulomb failure criterion for soft soil and sand were used to model the Elasto-Perfectly plastic behaviour of the gravelly sand and soft clay material response under loading conditions (Brinkgreve and Broere, 2015; Meghzili *et al.*, 2017).

The Response Surface Method (RSM) was designed by Box and Wilson (1951) as a collection of statistical and mathematical techniques used for developing, improving and optimising processes through empirical model building (Powrel, 2014). Response surface methodology involves the practice of adjusting the predictor variables to move the response to an optimum level via iteration in a desired direction (Wani and Kumar, 2016). The method usually includes an integration of both visualisation and computation. The RSM contains the design of response surface analysis and experiments. It typically supports the design of experiments to ascertain a set of design variables which will lead to response optimisation (Kola, 2014). Fitting and identifying an appropriate RSM model from experimental data require some knowledge of elementary optimisation methods, the fundamentals of statistical experimental design and techniques in regression modelling (Subramaniam, 2011). The widespread applications of RSM occurs in the industrial world, particularly in situations where several input variables theoretically influence the quality characteristics of the product or performance measure process (Powrel, 2014). These quality characteristics or performance measures are called as the response which are typically measured on sensory responses and ranks although the attributed responses and continuous scale are common in these regards. Most practical applications of the RSM involve more than one response. The input variables are sometimes referred to as the independent variables which are subjected to the manipulation of the scientist or engineer, at least for purposes of an experiment or a test.

1.2 Problem statement

The constructions of commercial properties, residential buildings, road and railway networks at very thick and soft ground of more than 40 m can lead to a high cost of ground improvement (Yusof, 2012). Among the ground improvement methods applied for thicker soft ground is stiffening stone column. Stiffening stone column is often considered environmentally friendly due to partial removal of soft material and replacement with crushed stone to achieve the design load bearing capacity and allowable settlement. Traditionally, the installation of stone column is always designed to reach stiff layers that have a shear strength of more than 50 kPa (Priebe, 1995). For economical design, the stiff layer should be at a depth between 6 m and 10 m (Shahrokhifard and Poursalehan, 2015). According to Salahi, Niroumand, and Kassim (2015), it is non-economical if the length of the stone column is more than 10 m. According to Keller (2004), it is not recommended to install the stone columns to up to 30 m in depth. However, there are some construction sites in the U.S.A. and Europe have constructed the stone columns up to 21 m in length (Shahrokhifard and Poursalehan, 2015). Lately, constructors are interested to adopt the floating stone columns in dealing with very thick soft ground to reduce the construction cost and the associated limitation of using machines to reach a deeper layer. Some researchers (Sivakumar *et al.*, 2007; Black, 2007; Killeen, 2012; Kelly, 2014) have conducted studies on floating stone column to indicate that an increase in the column diameter will cause the increment in the load bearing capacity. Moreover, an increase in the column length leads to a decrease in the settlement. However, none of the current study on incorporates the idea of hybrid column size of floating stone column. A better understanding of the hybrid column size is required in order to achieve maximum load bearing capacity and minimum ground settlement for floating stone column. Therefore, the behaviour of the floating stone column in terms of its bearing capacity and settlement need to be thoroughly examined in this study thus emphasising the novelty of the current work. Another issue exists in the stone column installation is it uses an excessive volume of the coarse aggregate in uniform column diameter.

1.3 Aim and objectives of research

The aim of this study is to evaluate the hybrid column size of the floating stone columns as well as the reduction of aggregate volume in order to increase the load bearing capacity and reduce the settlement. To achieve this aim, the following objectives are identified:

Ⅰ. To perform the combination of diameter and length of uniform stone column in order to optimise the performance of floating stone column determined by numerical model using Response Surface Methodology (RSM).

Ⅱ. To establish the prediction model of the load bearing capacity and settlement of soft clay reinforced with the hybrid column size of the floating stone column by numerical model using Response Surface Methodology (RSM).

Ⅲ. To verify the performance of hybrid column size of the floating stone column determined numerically by physical model.

1.4 Scope of Study

The numerical and physical testing designed for this research is modelling a single stone column in soft clay to be loaded statically for the study of its short-term behaviour. This study provides details of materials, apparatus and method employed in the preliminary testing and main testing of the stone column evaluations (numerical and physical). This study initially started with examining the material properties and behaviour of kaolin and gravelly sand. These material were chosen as the base soil for this study. The kaolin compaction tests were conducted by using the BS 1377-4: 1990 method. Meanwhile, for gravelly sand, the compaction tests were carried out by using the vibrating hammer method as described in BS 1377-4:1990 (BSI, 1990). Kaolin and gravelly sand have maximum dry density of about 1365.76

kg/m^3 and 1816.5 kg/m^3 at optimum water content of 32 % and 9 % respectively. In addition, the kaolin was mixed with several percentage of water content to determine the shear strength by vane shear tests which summarized in section 3.3.7. According to the relationship between shear strength and water content that summarized in Figure 3.5, the kaolin was chosen to be mixed with 42 % of water content in order to produce soft clay with 15 kpa. Triaxial consolidated-undrained and Consolidated-drained test (CU and CD) test to collect parameters of soft clay and gravelly sand which required in numerical model according to Mohr-coulomb of constitutive model.

The pilot part of the simulation program was employed to allow assessment of uniform column performance and the relationship between factors (diameter and length) and responses (load bearing capacity and settlement). The initial test was evaluated by numerical modelling using Plaxis 2D and optimized by response surface methodology (RSM) to reduce the cost of experimental and as an alternative to conventional design methods. The main simulation was divided into two stages. First stage is a numerical evaluation of the load bearing capacity and settlement of hybrid column size testing program using Plaxis 2D as well to optimising the results with the use of Design-Expert 6.0.4 software (full details can be found in chapter 4). All of the numerical modelling were evaluated to obtain the optimum design of stone column in order to increase the load bearing capacity and reduce the settlement of soft clay. Second category was the physical testing is employed by automated compression test to evaluate the optimum design of stone column that was achieved from numerical modelling to verify the results.

1.5 Importance of study

This study is important to provide criterion of soft ground and the floating column dimension such as diameter and length in order to increase the load bearing capacity and reduce settlement. This optimum design of the floating stone column with dual dimension of diameter and length is able to reduce the construction cost via minimisation of coarse aggregate usage. The contributions of this research are as follows;

i. This research explains and understands that the diameter and length of stone column influence the load bearing capacity and settlement respectively with respect to the real design dimensions.
ii. The hybrid column size of floating stone column is developed to increase the load bearing capacity and reduce the settlement by using 40 % less stone amount than previous uniform installation at numerical (Plaxis 2D) with the help of RSM optimisation and established laboratory scale.
iii. This research introduces equations to obtain a high load bearing capacity and low settlement of floating stone column for its reliability.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The information of the stone column as a common ground improvement method will be provided in this chapter. The discussion of the behaviour and impact of the stone column design on the performance of the stone column are critically reviewed. This chapter arranges a general review of stone column techniques highlighting the factors that the most important influences that can affect the performance in short term will be further discussed in chapter 3.

2.2 Ground improvement

According to the ground improvement methods, one of the main practices of geotechnical engineering is to design, evaluate and implement ground improvement for infrastructure projects. Over the past 25 years, a considerable amount of new technologies has been widely implemented and developed to assist geotechnical specialists in providing cost-effective solution for the construction of marginal or difficult grounds. The ground improvement method discussed is based on the content of the ground improvement method since appropriate floor area is not always viable and the engineers are required to execute modification according to the technical requirements of each project (Zomorodian *et al.*, 2005). However, since the new technology is always evaluated, the proposed concept should not be seen as a comprehensive discussion of ground improvement methods (Charles and Watts, 2002). In addition, environmental issues have started to become increasingly

REFERENCES

Aboshi, H., Ichimoto, E., Enoki, M., & Harada, K. (1979). *The compozer—a method to improve characteristics of soft clays by inclusion of large diameter sand columns.* Proc., Int. Conf. on Soil Reinforcement: Reinforced Earth and Other Techniques, Champs-sur-Marne France: Ecole des Ponts ParisTech/Laboratoire Central des Ponts et Chaussées (ENPC/LCPC), 211-216.

Aboshi, H., Mizuno, Y., & Kuwabara, M. (1991). Present state of sand compaction pile in Japan *Deep Foundation Improvements: Design, Construction, and Testing*: ASTM International.

Abusharar, S. W., Zheng, J., Chen, B., & Yin, J. (2009). A simplified method for analysis of a piled embankment reinforced with geosynthetics. *Geotextiles and Geomembranes, 27*(1), 39-52.

Adalier, K., & Elgamal, A. (2004). Mitigation of liquefaction and associated ground deformations by stone columns. *Engineering Geology, 72*(3), 275-291.

Ahmad, Y., Amran, G., & Chin, N. (2008). Problems and Solutions in Statistics for Engineers and Scientists. *Pearson Prentice-Hall, 299 pp.*

Al-Taie, E., Al-Ansari, N., & Knutsson, S. (2016). Evaluation of Foundation Settlement under Various Added Loads in Different Locations of Iraq Using Finite Element. *Engineering, 8*(5), 257-268.

Al Ammari, K. (2016). *Predicting Stiffness and Stress Variation of Saturated Clay Improved with Vibro Stone Columns and Evaluating its Effect on Improving Reinforced Foundations.* University of Leeds.

Aliabadian, Z., & Sharafisafa, M. (2014). Numerical modeling of presplitting controlled method in continuum rock masses. *Arabian Journal of Geosciences*, *7*(12), 5005-5020.

Alpaslan, B., Bilge, Y., & Mehmet, A. (2002). Remediation of lead contaminated soils by stabilization/solidification. *Water, Air, & Soil Pollution, 133*(1), 253-263.

Ambily, A., & Gandhi, S. R. (2007). Behavior of stone columns based on experimental and FEM analysis. *Journal of geotechnical and geoenvironmental engineering*, *133*(4), 405-415.

Amini, R. (2016). *Physical modelling of vibro stone column using recycled aggregates.* University of Birmingham: Ph.D. Thesis.

Andreou, P., Frikha, W., Frank, R., Canou, J., Papadopoulos, V., & Dupla, J. (2008). Experimental study on sand and gravel columns in clay. *Proceedings of the Institution of Civil Engineers-Ground Improvement, 161*(4), 189-198.

Andreou, P., & Papadopoulos, V. (2006). Modelling stone columns in soft clay. *Proc. 6th European Conf. on Numerical Methods in Geotechnical Engineering, Graz, 777–780*.

Aqil, U., Tatsuoka, F., Uchimura, T., Lohani, T. N., Tomita, Y., & Matsushima, K. (2005). Strength and deformation characteristics of recycled concrete aggregate as a backfill material. *Soils and Foundations, 45*(5), 53-72.

Ayadat, T., Hanna, A. M., & Hamitouche, A. (2008). Soil improvement by internally reinforced stone columns. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, *161*(2), 55-63.

Aza-Gnandji, R., & Kalumba, D. (2014). Experimental and numerical analyses of the behavior of rammed stone columns installed in a South African Soft Soil. *International Journal of Engineering Science and Innovative Technology, 3*(6).

Aza, R., & Kalumba, D. (2014). Experimental and numerical analyses of the behavior of rammed stone columns installed in a South African Soft Soil. *International Journal of Engineering Science and Innovative Technology, 3*(6).

Bachus, R., & Barksdale, R. (1984). *The behavior of foundations supported by clay stabilized by stone columns.* Eighth European conference on soil Mechanics and Foundation Engineering Helsinki: 199-204.

Balaam, N., & Booker, J. R. (1981). Analysis of rigid rafts supported by granular piles. *International Journal for Numerical and Analytical Methods in Geomechanics, 5*(4), 379-403.

Balaam, N., Brown, P., & Poulos, H. (1977). *Settlement analysis of soft clays reinforced with granular piles.* 5th Southeast Asian Conference on Soil Engineering, , Bangkok, Thailand:

Balaam, N., & Poulos, H. (1978). Methods of analysis of single stone columns *No. Research Rpt. R335 Monograph*.

Barksdale, R., & Bachus, R. (1983). *Design and construction of stone columns Volume II, Appendixes*: Federal Highway Administration Washington, DC, USA.

Barksdale, R., & Bachus, R. (1984). *Vertical and lateral behaviour of model stone columns.* Proc. Int. Conf. on In-situ Soil and Rock Reinforcement:

Barrak, N., Mannai, R., Zaidi, M., Kechida, M., & Helal, A. N. (2016). Experimental Design Approach with Response Surface Methodology for Removal of Indigo Dye by Electrocoagulation. *Journal of Geoscience and Environment Protection*, *4*(11), 50.

Baumann, V., & Bauer, G. (1974). The performance of foundations on various soils stabilized by the vibro-compaction method. *Canadian Geotechnical Journal, 11*(4), 509-530.

Becker, P. (2013). Importance of observational method in view of numerical analyses for retaning structures in soft soils. *International Conference on Case Histories in Geotechnical Engineering: Chicago, Illinois, 28.*

Bell, A. (2004). The development and importance of construction technique in deep vibratory ground improvement. *Ground and soil improvement*, *3*, 101-111.

Black, J. (2007). The settlement performance of a footing supported on soft clay reinforced with vibrated stone columns. *Queen's University of Belfast, Northern Ireland: Ph.D. Thesis*.

Black, J., Sivakumar, V., & Bell, A. (2011). The settlement performance of stone column foundations. *Geotechnique*, *61*(11), 909-922.

Black, J. A., McNeill, J. A., & McCabe, B. A. (2007). Ground improvement using the vibro-stone column technique. *Meeting of Engineers and the Geotechnical Society. Ireland West Region, NUI Galway: Institution of Engineers*.

Box, G., & Wilson, K. (1951). Royal Statistical Society–Series B. *Statistical Methodology*, *13*, 1.

Bradley, N. (2007). *The response surface methodology*. Indiana University South Bend: Master's Thesis.

Brauns, J. (1978). *Initial bearing capacity of stone columns and sand piles.* Int. Symp. on Soil Reinforcing and Stabilizing Techniques in Engineering Practice: 497-512.

Brinkgreve, R. (2004). *PLAXIS: 3D Foundation, Version 1 Reference Manual*: Balkema.

Brinkgreve, R., & Broere, W. (2015). PLAXIS 2D Reference Manual 2015. *Delft, Netherlands 2010*.

Brinkgreve, R., Engin, E., & Swolfs, W. (2014). PLAXIS 2014. *PLAXIS bv, The Netherlands*.

Brinkgreve, R., & Swolfs, W. (2004). Plaxis 3D Foundation Version 2, Reference Manual: AA Balkema Publishers Lisse/Abindgdon/Exton (Pa)/Tokyo.

BSI, B. (1990). Methods of test for soils for civil engineering purposes. *BS1377*.

Charles, J., & Watts, K. (1983). *Compressibility of soft clay reinforced with granular columns.* Proceedings of the 8th European conference on soil mechanics and foundation Engineering, Helsinki: 347-352.

Charles, J., & Watts, K. (2002). *Treated ground: engineering properties and performance; CIRIA C572*: CIRIA.

Clarke, B. G. (1994). *Pressuremeters in geotechnical design*: CRC Press.

Clayton, C. R., Matthews, M. C., & Simons, N. E. (1995). *Site investigation: a handbook for engineers*: Blackwell Science.

Cooper, M., & Rose, A. (1999). Stone column support for an embankment on deep alluvial soils. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 137*(1), 15-25.

Curtin, W., Shaw, G., Parkinson, G., & Golding, J. (2006). Ground improvement methods. *Structural Foundation Designers' Manual*, 124-139.

Davis, J. R. (2004). *Handbook of thermal spray technology*: ASM international.

Debnath, P., & Dey, A. K. (2017). Bearing capacity of geogrid reinforced sand over encased stone columns in soft clay. *Geotextiles and Geomembranes, 45*(6), 653-664.

Diarra, H., Mazel, V., Busignies, V., & Tchoreloff, P. (2017). Comparative study between Drucker-Prager/Cap and modified Cam-Clay models for the numerical simulation of die compaction of pharmaceutical powders. *Powder Technology, 320*, 530-539.

Egan, D., Kamrat, P. D., & McCabe, B. A. (2013). Ground heave induced by installing stone columns in clay soils. *Proceedings of ICE geotechnical engineering*.

Egan, D., & Slocombe, B. (2010). Demonstrating environmental benefits of ground improvement. *Ground improvement. Proceedings of the Institution of Civil Engineers, 163*(1).

Fang, Q., Tsuchiya, T., & Yamamoto, T. (2002). Finite difference, finite element and finite volume methods applied to two-point boundary value problems. *Journal of Computational and Applied Mathematics, 139*(1), 9-19.

Fattah, M. Y., Zabar, B. S., & Hassan, H. A. (2016). Experimental analysis of embankment on ordinary and encased stone columns. *International Journal of Geomechanics, 16*(4), 04015102.

Floros, J., & Chinnan, M. (1988). Computer graphics- assisted optimization for product and process development. *Food Technology, 42*(2), 72-78.

Ghazavi, M., & Afshar, J. N. (2013). Bearing capacity of geosynthetic encased stone columns. *Geotextiles and Geomembranes, 38*, 26-36.

Gibson, R. (1961). In situ measurement of soil properties with the pressuremeter. *Civil Engrg. and Pub. Wks. Rev, 56*(568), 615-618.

Greenwood, D. (1900). *Mechanical improvement of soils below ground surface.* Inst Civil Engineers Proc, London/UK/:

Han, J. (2015). *Principles and practice of ground improvement*: 1118259912. Canada. John Wiley & Sons.

Hanna, A., Etezad, M., & Ayadat, T. (2013). Mode of failure of a group of stone columns in soft soil. *International Journal of Geomechanics, 13*(1), 87-96.

Hasan, M., & Samadhiya, N. (2017). Performance of geosynthetic-reinforced granular piles in soft clays: Model tests and numerical analysis. *Computers and Geotechnics, 87*, 178-187.

Hezmi, A., Rashid, A., & Alel, M. A. (2015). Performance prediction of prefabricated vertical drain in soft soil using finite element method. *Jurnal Teknologi (Sciences & Engineering)*, 67-72.

Hicher, P. Y., & Shao, J. F. (2013). *Constitutive modeling of soils and rocks*: Canada: John Wiley & Sons.

Howard, I. L., & Warren, K. A. (2009). Finite-element modeling of instrumented flexible pavements under stationary transient loading. *Journal of Transportation Engineering, 135*(2), 53-61.

Hu, W. (1995). *Physical modelling of group behaviour of stone column foundations.* University of Glasgow, UK: Ph.D. Thesis.

Hughes, J., & Withers, N. (1974). Reinforcing of soft cohesive soils with stone columns. *Ground engineering, 7*(3).

Hughes, J., Withers, N., & Greenwood, D. (1975). A field trial of the reinforcing effect of a stone column in soil. *Geotechnique, 25*(1), 31-44.

Hurley, O., Nuth, M., & Karray, M. (2015). Finite element modelling of stone column installation: Review of modelling practices and case study with Plaxis 2D. *Challenges from North to South des defis du nord au sud, GEO Quebec, Canada*.

Ing, C. D., Baker, C. J., Fiht, F., Ghea, M., Dis, D. C., Jefferson, D., & Cmath, C. (2012). Resistance and resilience-paradigms for critical local infrastructure. *Proceedings of the Institution of Civil Engineers, 165*(2), 73.

Jardine, R., Potts, D., Fourie, A., & Burland, J. (1986). Studies of the influence of non-linear stress–strain characteristics in soil–structure interaction. *Geotechnique, 36*(3), 377-396.

Jebe, W., & Bartels, K. (1983). *The development of compaction methods with vibrators from 1976 to 1982.* 8th European Conference on Soil Mechanics and Foundation Engineering:

Jianhong, Y., Dongsheng, J., Ren, W., & Changqi, Z. (2013). Numerical study of the stability of breakwater built on a sloped porous seabed under tsunami loading. *Applied Mathematical Modelling, 37*(23), 9575-9590.

John, U. E. (2011). *Chemical performance of cement stabilised contaminated clay.* University of Birmingham: Ph.D. Thesis.

Keller, W. (2004). International technology diffusion. *Journal of economic literature, 42*(3), 752-782.

Kelly, P. (2014). *Soil structure interaction and group mechanics of vibrated stone column foundations.* University of Sheffield: Ph.D. Thesis.

Killeen, M. (2012). *Numerical modelling of small groups of stone columns.* National University of Ireland, Galway: Ph.D. Thesis.

Kirsch, F. (2006). *Vibro stone column installation and its effect on ground improvement.* Proceedings of the International Conference on Numerical Modelling of Construction Processes in Geotechnical Engineering for Urban Environment: 115-124.

Kirsch, F., & Sondermann, W. (2003). *Field measurements and numerical analysis of the stress distribution below stone column supported embankments and their stability*. International Workshop on Geotechnics of Soft Soils-Theory and Practice: 17-19.

Kirsch, K., & Kirsch, F. (2016). *Ground improvement by deep vibratory methods*: CRC Press.

Klein, E., & Tobin, R. (1996). Design & Construction of Deep Stone Columns in Marine Clay at Spectacle Island. *CIVIL ENGINEERING PRACTICE-BOSTON-*, *11*, 79-94.

Kola, N. (2014). *Reliability based analysis of dam embankment, geocellreinforced foundation and embankment with stone columns using finite element method.* National Institue of Technology, Rourkela, India: Master's Thesis.

Kumar, M., Ponselvan, I. A., Malviya, J. R., Srivastava, V. C., & Mall, I. D. (2009). Treatment of bio-digester effluent by electrocoagulation using iron electrodes. *Journal of hazardous materials*, *165*(1-3), 345-352.

Leung, C., Yee, Y., & Leong, K. (2015). Principles and case histories of deep vibro techniques. *Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics*, 337.

Liew, S., & Tan, S. (2007). *Performance of reinforced soil wall supported on stone Columns.* Proc. 16 th Southeast Asian Geotechnical Conferences, Malaysia:

Lovisa, J., Shukla, S. K., & Sivakugan, N. (2010). Behaviour of prestressed geotextile-reinforced sand bed supporting a loaded circular footing. *Geotextiles and Geomembranes*, *28*(1), 23-32.

Madun, A. (2012). *Seismic evaluation of vibro-stone column.* University of Birmingham: Ph.D. Thesis.

Malarvizhi, S. (2007). Comparative study on the behavior of encased stone column and conventional stone column. *Soils and Foundations, 47*(5), 873-885.

Manual, P. (2008). Material models manual. *Delft University of Technology & PLAXIS bv, The Netherlands*.

Marfurt, K. J. (1984). Accuracy of finite-difference and finite-element modeling of the scalar and elastic wave equations. *Geophysics, 49*(5), 533-549.

McCabe, B., & Bryan, A. (2009). A review of field performance of stone columns on soft soils. *Proceedings of ICE geotechnical engineering*.

McCabe, B., Bryan, A., & Sheil, B. (2014). Pile group settlement estimation: suitability of nonlinear interaction factors. *International Journal of Geomechanics, 15*(3), 04014056.

McKelvey, D. (2002). *The performance of vibro stone column reinforced foundations in deep soft ground.* Queen's University of Belfast: Ph.D. Thesis.

McKelvey, D., & Sivakumar, V. (2000). *A review of the performance of vibro stone column foundations.* Proceedings of the 3rd International Conference on Ground Improvement Techniques, Singapore: 25-26.

McKelvey, D., Sivakumar, V., Bell, A., & Graham, J. (2004). Modelling vibrated stone columns in soft clay. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 157*(3), 137-149.

Meghzili, S. A., Madun, A., Tajudin, S. A. A., Yusof, M. F., & Ismail, M. A. M. (2017). *Numerical evaluation on the different shapes of gravelly sand columns to increase the loading capacity of soft clay.* MATEC Web of Conferences: EDP Sciences 07005.

Meyerhof, G. (1961). The ultimate bearing capacity of wedge-shaped foundations-La force portante des fondations en coins. *Technical Memorandum, Division of Building Research, National Research Council Canada*(72-9), 1-5.

Mitchell, J. K., & Huber, T. R. (1985). Performance of a stone column foundation. *Journal of Geotechnical Engineering, 111*(2), 205-223.

Mitchell, J. M., & Jardine, F. M. (2002). *A guide to ground treatment* (Vol. 573): CIRIA London.

Mohanty, P., & Samanta, M. (2015). Experimental and numerical studies on response of the stone column in layered soil. *International Journal of Geosynthetics and Ground Engineering, 1*(3), 27.

Munfakh, G. (1984). *Soil reinforcement by stone columns-varied case applications.* Int. Conference on Insitu Soil and Rock Reinforcement: pp. 157-162.

Murugaiah, A. (2004). Nanoindentations in kinking nonlinear elastic solids. *Drexel University, Philadelphia, USA: Ph.D. Thesis*.

Murugesan, S., & Rajagopal, K. (2007). Model tests on geosynthetic-encased stone columns. *Geosynthetics International, 14*(6), 346-354.

Naik, J. K. (2013). *Load carrying capacity of stone columns embedded in compacted pond ash.* National Institute of Technology Rourkela-769008, Orissa, India: Master's Thesis.

Narasimha, R. S., Prasad, Y., & Hanumanta R, V. (1992). *Use of stone columns in soft marine clays.* Proceedings of the 45th Canadian Geotechnical Conference, Toronto, Ont: 26-28.

Nicholson, P. G. (2014). *Soil improvement and ground modification methods*: USA: Butterworth-Heinemann.

Oehlert, G. W. (2000). Design and analysis of experiments: Response surface design. *Book, University of Minnesota, New York*.

Oh, E., Balasubramaniam, A., Surarak, C., Bolton, M., Chai, G., Huang, M., & Braund, M. (2007). *Behaviour of a highway embankment on stone columns improved estuarine clay*. Proc., 16th Southeast Asian Geotechnical Conf: 567-572.

Olsson, M. (2013). *On rate-dependency of Gothenburg clay*: Chalmers University of Technology Gothenburg, Gothenburg, Sweden: Ph.D. Thesis.

Pande, G., Lee, J., & Amaniampong, G. (1994). *A Numerical model for stone-column reinforced foundations*: University College of Swansea, Department of Civil Engineering.

Peiró, J., & Sherwin, S. (2005). Finite difference, finite element and finite volume methods for partial differential equations. *Handbook of materials modeling*, 2415-2446.

Pivarč, J. (2011). Stone Columns-Determination of the soil improvement factor. *Slovak journal of civil engineering, 19*(3), 17-21.

Potts, D. M., Zdravkovic, L., & Zdravković, L. (2001). *Finite element analysis in geotechnical engineering: application* (Vol. 2): Imperia College of Science, Technology and Medicine, Thomas Telford: Theory.

Powrel, D. B. (2014). *Optimizing electrocoagulation process for treatment of biodiesel wastewater using response surface method.* Ph.D. Thesis.

Priebe, H. (1976). Evaluation of the settlement reduction of a foundation improved by Vibro-Replacement. *Bautechnik, 5*, 160-162.

Priebe, H. (2005). Design of vibro replacement. *Ground engineering, 38*(1).

Priebe, H. J. (1995). The design of vibro replacement. *Ground engineering, 28*(10), 31.

Raju, V., Masud, A., & Ha, P. (1997). *Vibro replacement-a technique for extensive ground improvement works in very soft cohesive soils at the Shah Alam Expressway.* 4th Geotechnique-Colloquium, Malaysia:

Raju, V., & Sondermann, W. (2005). Ground improvement using deep vibro techniques. *Elsevier Geo-Engineering Book Series, 3*, 601-638.

Raju, V., & Valluri, S. (2008). *Practical applications of ground improvement.* Symposium on Engineering of ground & Environmental Geotechnic (S EG2), Hyderabad, 29th Feb:

Raju, V., Wegner, R., & Krishna, Y. H. (2004). *Ground Improvement Using Vibro Replacement in Asia 1994 to 2004.* 5 th International Conference on Ground Improvement Techniques. Kuala Lumpur, Malaysia:

Randolph, M. F., Carter, J., & Wroth, C. (1979). Driven piles in clay—the effects of installation and subsequent consolidation. *Geotechnique, 29*(4), 361-393.

Roscoe, K. H., & Burland, J. (1968). On the generalized stress-strain behaviour of wet clay. *Geotechnology; Highways; Road Research Laboratory, UK*, pp 535-609.

Salahi, A., Niroumand, H., & Kassim, K. A. (2015). Evaluation of stone columns versus liquefaction phenomenon (Vol. Vol. 20): EJGE, Department of Civil Engineering, Faculty of Engineering, Islamic A. University, Tehran, Iran.

Sathishbalamurugan, M., & Muhunthan, B. (2008). Modelling embankments reinforced with sand columns. *Proceedings of the Institution of Civil Engineers-Ground Improvement, 161*(2), 71-78.

Serridge, C. J. (2006). Sustainability in the context of vibro stone column ground improvement techniques. *Proceedings of the 5th ICEG-environmental geotechnics opportunities, challenges and responsibilities for environmental geotechnics , Cardiff, Vols 1 and 2.* .

Serridge, C. J. (2013). *An evaluation of partial depth dry bottom-feed vibro stone columns to support shallow footings in deep soft clay deposits.* Anglia Ruskin University, East Anglia, United Kingdom: Ph.D. Thesis.

Sexton, B. (2014). *The influence of creep on the settlement of foundations supported by stone columns.* National University of Ireland, Galway:: Ph.D. Thesis.

Shahrokhifard, H., & Poursalehan, S. J. (2015). Evaluation of the effective components in the survey of types of liquefaction. *Current World Environment, 10*(Special Issue 1), 326-332.

Shien, N. K. (2013). Cavity expansion approach In modelling stone column installation effect. *International Journal of Advances in Engineering Science and Technology, 2*(2), 252-260.

Shivashankar, R., Babu, M. D., Nayak, S., & Manjunath, R. (2010). Stone columns with vertical circumferential nails: laboratory model study. *Geotechnical and Geological Engineering, 28*(5), 695-706.

Shivashankar, R., Babu, M. D., Nayak, S., & Rajathkumar, V. (2011). Experimental studies on behaviour of stone columns in layered soils. *Geotechnical and Geological Engineering, 29*(5), 749.

Simpson, B., & Tatsuoka, F. (2008). Geotechnics: the next 60 years *The essence of geotechnical engineering: 60 years of géotechnique* (pp. 49-60): Thomas Telford Publishing.

Simpson, M., & Clement, T. (2003). Theoretical analysis of the worthiness of Henry and Elder problems as benchmarks of density-dependent groundwater flow models. *Advances in Water Resources, 26*(1), 17-31.

Sivakumar, V., Glynn, D., Black, J., & McNeill, J. (2007). *A laboratory model study of the performance of vibrated stone columns in soft clay.* Proceedings of the 14th European conference on soil mechanics and geotechnical engineering, Madrid, Spain: 24-27.

Sivakumar, V., McKelvey, D., Graham, J., & Hughes, D. (2004). Triaxial tests on model sand columns in clay. *Canadian Geotechnical Journal, 41*(2), 299-312.

Slocombe, B., Bell, A., & Baez, J. (2004). The densification of granular soils using vibro methods *Ground and soil improvement* (pp. 153-163): Thomas Telford Publishing.

Som, M., & Das, S. (2003). *Theory and practice of foundation design*: PHI Learning Pvt. Ltd.

Sondermann, W., & Wehr, W. (2004). Deep vibro techniques. *Ground Improvement, 2*, 57-92.

Steele, D. (2004). Ground Engineering as potential end uses for recycled and secondary aggregates. *The Waste & Resources Action Programme*.

Stewart, W., & Hu, W. (1993). Analysis of Regularly Inhomogenious Soils–Report on Pilot Tests. *Glasgow. Dept. Civ. Engg. University of Glasgow*.

Subramaniam, P. (2011). *Reliability based analysis of slope, foundation and retaining wall using finite element method.* Ph.D. Thesis.

Tajudin, A. A. S. (2012). *Electrokinetic stabilisation of soft clay*. University of Birmingham: Ph.D. Thesis.

Vesic, A. S. (1972). Expansion of cavities in infinite soil mass. *Journal of Soil Mechanics & Foundations Div, 98*(sm3).

Waltham, T. (2009). *Foundations of engineering geology*: CRC Press.

Wani, S., & Kumar, P. (2016). Fenugreek enriched extruded product: optimization of ingredients using response surface methodology. *International Food Research Journal, 23*(1).

Watts, K. (2000). Specifying vibro stone columns. *British Research Establishment (BRE) Report, Watford, UK*.

Weber, T., Laue, J., & Springman, S. (2006). *Centrifuge modelling of sand compaction piles in soft clay under embankment load.* International Conference on Physical Modelling in Geotechnics: 04/08/2006-06/08/2006: 603-608.

Wehr, J. (2006). *The undrained cohesion of the soil as criterion for the column installation with a depth vibrator.* Proceedings of the international symposium on vibratory pile driving and deep soil Vibratory compaction. TRANSVIB, Paris: 157-162.

Winer, B. J. (1971). Multifactor experiments having repeated measures on the same elements. *Statistical principles in experimental design*, 514-603.

Wood, M. D., Hu, W., & Nash, D. (2000). Group effects in stone column foundations: model tests. *Geotechnique, 50*(6), 689-698.

Woodward, J. (2005). *An introduction to geotechnical processes*: CRC Press.

Yoo c, K. S. B. (2009). Numerical modeling of geosynthetic-encased stone column-reinforced ground. *Geosynthetics International, 16*(3), 116-126.

Yusof, M. (2012). *Composite foundations on Malaysian soft clay soil: applications of innovative techniques.* University of Leeds: Ph.D. Thesis.

Zienkiewicz, O., Kelly, D., & Bettess, P. (1977). The coupling of the finite element method and boundary solution procedures. *International Journal for Numerical Methods in Engineering, 11*(2), 355-375.

Zomorodian, Ali, E., & Abolfazle. (2005). Determining the geotechnical parameters of stabilized soils by stone column based on SPT results. *J. Geotech. Eng*, *10*.